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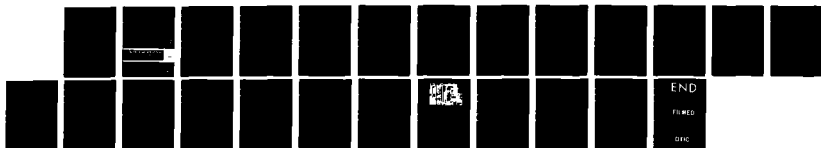
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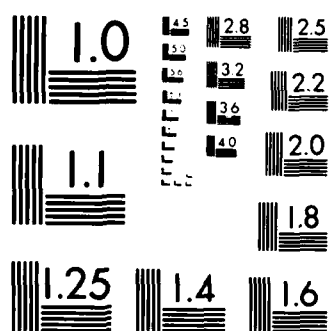
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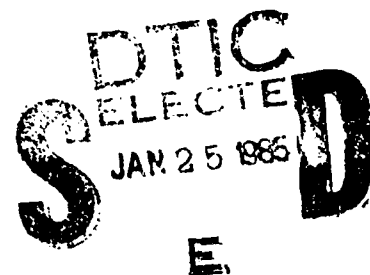
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Annual Progress Report
on

Fracture Toughness of
Fiber Reinforced Concrete

AFOSR - 82-0243

Principal Investigator: S. P. Shah



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beam test is detailed in the attached summary paper (Item 7). Notched-beam specimens of three different sizes and five different materials composites were tested to develop the proposed theoretical model. Beams were tested in a closed-loop testing system using the crack mouth opening displacement as a feed-back control. Crack growth was microscopically monitored. The details are given in Item 7. It was observed that the nonlinear critical stress intensity factor (as defined here) was independent of the size of the specimen and was constant during the post-critical crack growth.

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1. Summary

→ The primary accomplishment during the reporting period was the development of nonlinear fracture criteria for cement-based composites. These fracture criteria accurately predict two important aspects of crack growth in concrete, fiber reinforced concrete and other cement-based composites: (1) nonlinear process zone and (2) quasi-stable crack growth beyond the peak load. A preexisting crack in a concrete structure propagates in two stages: subcritical crack growth, and beyond the peak load, post-critical crack growth. The second stage can only be observed if the structure is loaded in a displacement-controlled mode. As a result of the nonlinear subcritical crack growth, when the fracture toughness of a concrete specimen (for example, notched-beam) is determined using conventional linear elastic fracture mechanics, different values are observed depending upon the size of the specimen.

A size-independent critical stress intensity factor and critical crack-tip opening displacement are proposed as fracture toughness criteria for the concrete. To evaluate these two parameters, nonlinear deformations must be extracted from the total displacement. How to evaluate these two parameters from the three-point notched beam test is detailed in the attached summary paper (Item 7).

Notched-beam specimens of three different sizes and five different materials composites were tested to develop the proposed theoretical model. Beams were tested in a closed-loop testing system using the crack mouth opening displacement as a feed-back control. Crack growth was microscopically monitored. The details are given in Item 7. It was observed that the nonlinear critical stress intensity factor (as defined here) was independent

of the size of the specimen and was constant during the post-critical crack growth.

2. Research Objective

To develop rational methods to predict fracture toughness of fiber reinforced concrete is the primary goal of this investigation. It is known that the addition of randomly distributed, short, steel fibers substantially enhances the crack propagation resistance of concrete. How to experimentally evaluate this critical property of fiber reinforced concrete and how to rationally predict it are the objectives of this research.

3. Status of the Research

A method is developed to predict crack propagation in unreinforced matrix. This method was based on experimental results of notched-beam specimens.

The closed-loop notched-beam tests are now being conducted for fiber reinforced concrete. The theoretical model developed for plain concrete will be extended for fiber reinforced concrete. The theoretical model proposed is for Mode I crack propagation. Attempts are being made to extend it to mixed-mode loading.

4. List of Publications

1. Wecharatana, M., and S. P. Shah, "A Model for Predicting Fracture Resistance of Fiber Reinforced Concrete," Cement and Concrete Research, November 1983, pp. 819-830.
2. Ballarini, R., S. P. Shah, and L. M. Keer, "Crack Growth in Cement Based Composites" Engineering Fracture Mechanics, (in press).

3. Jenq, Y. S., and S. P. Shah, "A Fracture Toughness Criterion for Concrete," Engineering Fracture Mechanics, (in press).
4. Jenq, Y. S., and S. P. Shah, "Nonlinear Fracture Mechanics for Cement Based Composites: Theory and Experiments", Proceedings of the NATO-ARW on Applications of Fracture Mechanics to Cementitious Composites, Sept. 4-7, 1984, Northwestern University, Ed., S. P. Shah
5. Ballarini, R., S. P. Shah, and L. M. Keer, "Nonlinear Analysis For Mixed Mode Fracture," Proceedings of the NATO-ARW on Applications of Fracture Mechanics to Cementitious Composites, Sept. 4-7, 1984, Northwestern University, Ed., S. P. Shah.
6. Stang, H., and S. P. Shah, "Failure of Fiber Reinforced Composites by Pull-Out Fracture," to be submitted for publication, Journal of Materials Science.
7. Jenq, Y. S., and S. P. Shah, "Crack Propagation in Fiber Reinforced Concrete," to be submitted for publication, Journal of Structural Engineering, (ASCE).
8. Jenq, Y. S., and S. P. Shah, "A Measure for the Fracture Toughness of Cement Based Materials," submitted, Proceedings, Symposium L. The Potential for Very High Strength Cement Based Materials., Boston, Nov. 26-30, 1984.

5. List of the Professional Personnel

| | |
|----------------|-------------------------------|
| Y. S. Jenq | Ph.D. Student |
| R. Ballarini | Ph.D. Candidate |
| A. Anandarajah | Post-doctoral Research Fellow |

6. Technical Presentations at the Following Professional Meetings

1. IUTAM William Prager Symposium on "Mechanics of Geomaterials; Rocks, Concretes, Soils," Northwestern University, September 1983.
2. Annual Convention of American Society of Civil Engineers - Structure Congress, Houston, October 17-19, 1983.

3. Annual Meeting, Transportation Research Board, Washington, D.C., January 1984.
4. NATO-Advanced Research Workshop on "Application of Frcture Mechanics to Cementitious Composites," Northwestern University, September 1984.
5. Symposium on the Potential for Very High Strength Cement Based Materials, Annual Meeting of Materials Research Society, Boston, November 1984.
6. Second Symposium on the Interaction of Non-Nuclear Munitions With Structures, Panama City, Florida, April 15-19, 1984.

7. Additional Information

To give some idea of the progress done during the report period, a paper which summarizes our nonlinear fracture mechanics model is attached. This paper will be presented at the Materials Research Society, Boston, November 26-30, 1984 and is submitted for publication in the proceedings of the Symposium.

A MEASURE FOR THE FRACTURE TOUGHNESS OF CEMENT BASED MATERIALS⁺

by

Y. S. Jenq¹ and S. P. Shah²

Department of Civil Engineering

Northwestern University

Evanston, Illinois, 60201

Introduction

It is frequently reported that the higher the strength of cement based materials, the more brittle is their behavior. It could be useful to quantitatively express the degree of brittleness. Many attempts [1-13] have been made to use linear elastic fracture mechanics (LEFM) to quantitatively express the degree of brittleness. For example, by testing notched beams one can calculate using the formulas developed from LEFM, a quantity called fracture toughness and termed K_{IC} from the measured maximum load and the initial notch-length. Unfortunately, it has been observed that K_{IC} thus calculated is dependent on the dimension of the beams. Many researchers have attempted to analyze this size dependency. Such approaches are usually quite cumbersome and are often based on expensive nonlinear finite element programs. In this paper a direct method is suggested to calculate two size-independent fracture toughness parameters from the experimental results. The method was developed based on tests on notched-beams of different mix proportions and different sizes.

Values of K_{IC}^S (critical stress intensity factor) and $CTOD_C$ (critical crack tip opening displacement) are suggested which appear to be size independent. The values of K_{IC}^S and $CTOD_C$ (Fig. 1) can be calculated based on the peak load, initial crack length (a_0) and the measured crack mouth opening displacement (CMOD). The calculation is based on the observation that nonlinear crack growth [14-22] occurs and that the elastic displacement

⁺For presentation at the Materials Research Society, November 26-30, 1984.

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displacement should be extracted from the total displacement to apply linear elastic fracture mechanics.

Based on the concept of constant K_{IC}^S and $CTOD_c$, theoretical prediction of load-CMOD relationships, size effect on modulus of rupture and conventional critical stress intensity factor (\bar{K}_{IC}) were compared with the experimental results and good correlations were observed.

Inelastic Displacement and Slow Crack Growth

A plot of load vs. crack mouth opening (CMOD) of a concrete beam obtained from the experiments (Fig. 2) can be used to describe the observed inelastic displacement and slow crack growth phenomena. A significant amount of inelastic displacement can be observed when the specimens are unloaded immediately after the peak load. The total crack mouth opening displacement ($CMOD^T$) is composed of a sum of the elastic crack mouth opening displacement without slow crack growth ($CMOD_0^e$), inelastic crack mouth opening displacement ($CMOD^*$), and the elastic crack mouth opening displacement due to slow crack growth ($CMOD_s^e$) (as shown in Fig. 2). The nonlinear displacement can be due to creep, microcracking and slow crack growth. For the short-term loading considered here, it is assumed that creep effect is negligible. The phenomenon of slow crack growth prior to the peak load has long been noticed. In addition to the geometrical interlock and microcracking resulting from the heterogeneous nature of concrete, the differences in the stress state along the crack front can also account for this observed slow crack growth. It has been noticed that the length of the crack front at the surface of the beams is longer than that at the interior. Thus, a channel shaped slow crack growth profile was observed by Swartz and Go [19]. Therefore, it is difficult to precisely measure the length of the crack at the peak load using optical measurement.

Determination of K_{IC}^S and $CTOD_c$ Using Three-Point Bend Tests

It is clear that in order to apply LEFM, the elastic crack mouth displacement ($CMOD^e = CMOD^T - CMOD^*$) should be extracted from the total displacement ($CMOD^T$). Also, to overcome the difficulties in measuring the exact length of the crack, an effective crack length is defined in this paper. The effective crack length (a) is the sum of the initial notch length (a_0) plus an effective crack extension (l_e). For a three-point bend test of notched-beam with span-depth ratio of four, the elastic crack

mouth opening displacement can be expressed by an empirical formula with accuracy of 1% error [23] as:

$$CMOD^e = \frac{6 P s}{b^2 t E'} V_1 \left(\frac{a}{b} \right) \quad (1)$$

where

$$V_1 \left(\frac{a}{b} \right) = 0.76 - 2.28A + 3.87A^2 - 2.04A^3 + \frac{0.66}{(1 - A)^2}$$

$$E' = \text{Young's modulus of elasticity, } A = \left(\frac{a}{b} \right)$$

P, s, a, b, t are indicated in Fig. 3.

For a given measured peak load (P_{max}), initial notch length (a_0) and the measured elastic $CMOD^e$, the effective crack length (a) is determined so that the calculated $CMOD^e$ is equal to the measured $CMOD^e$. Once the effective crack length is determined, then one can calculate using LEFM the values of K_{Ic}^S and $CTOD_c$. The K_{Ic}^S can be calculated as [23]

$$K_{Ic}^S = \frac{1.5 P_{max} s}{b^2 t} F_1 \left(\frac{a}{b} \right) \sqrt{\pi a} \quad (2)$$

in which

$$F_1 \left(\frac{a}{b} \right) = \frac{1}{\sqrt{\pi}} \frac{1.99 - A(1 - A)(2.15 - 3.93A + 2.7A^2)}{(1 + 2A)(1 - A)^{3/2}}$$

$$A = \frac{a}{b}$$

The value of $CTOD_c$ is the crack opening displacement at original notch tip and can be calculated using LEFM [26].

Note that K_{Ic}^S is not the same as the conventional critical stress intensity factor (\bar{K}_{Ic}) because calculation of K_{Ic}^S includes effects of slow crack growth and nonlinear displacement. To calculate K_{Ic}^S from test results, both the load and crack mouth opening displacement have to be monitored. Unlike the conventional \bar{K}_{Ic} values which were found to be size-dependent [1-8, 10-13], the values of K_{Ic}^S as well as $CTOD_c$ were found to be size-independent. In addition, using the constant values of

K_{IC}^S and $CTOD_C$ it was possible to accurately predict the load vs. CMOD (as well as load vs. load-point deflection) relationship for beams tested in this investigation as well as by other researchers [24, 25]. The theoretical justification for the validity of K_{IC}^S is given in Ref. 24.

Test Program and Experimental Details

Three point bend test was used to verify the validity of the proposed fracture criteria. Three different sizes of beams were used. These beams were designated as large (L), medium (M), and small (S). The span (s), depth (b), and thickness (t) for these beams were respectively; 36 in. (914mm), 9 in. (229mm), and 3.375 in. (85.7mm); 24 in. (609mm), 6 in. (152mm), 2.25 in. (57.2mm); and 12 in. (305mm), 3 in. (76mm), and 1.125 in. (28.6mm) (Fig. 3). Four series (C1, M1, M2, P1) of different mixes were prepared for studying the effect of the maximum aggregate size and water-cement ratio on the fracture toughness K_{IC}^S and $CTOD_C$. The notches were precast for C1, M1, M2 and P1 series and were saw cut for M3 series. All the initial notch-depth was equal to one-third of their depth. The beams were tested after curing for approximately 90 days (C1, M1, M2, and P1) and 75 days for M3 series in an environment with 96% relative humidity and 80°F (26.7°C). The mix proportions are listed in Table 1.

The large and medium size specimens were tested in a closed-loop servo controlled testing machine with a capacity of 120 Kips (534 KN) while the small beams were tested in a servo controlled closed-loop testing machine with a capacity of 20 Kips (89 KN). All notched beams were tested so as to maintain a constant rate of increase of CMOD, which was measured by a clip gage. The unnotched beams were tested by a constant rate of increase of deflection. The peak load was reached in about 10 minutes. During testing the deflection of the beam was measured by an LVDT located at about 1.5 to 2 in. (38 to 51mm) away from the notch and right under the center line of the beam. The surface crack length was monitored by a microscope with an accuracy of 0.001 in. (0.0025mm). The overall set-up is shown in Fig. 4. There were at least two beams for each size and mix proportion; a total of 46 beams were tested and analyzed. For each size and each mix proportion at least one beam was loaded cyclically.

Discussion of Test Results

Some of the test results are summarized in Table 2. Table 2 shows values of fracture toughness K_{IC}^S and $CTOD_C$ calculated using the procedure

described earlier. It can be seen that the values of K_{IC}^S as suggested here are independent of the size of the beam. This was not true for the values of the conventionally calculated \bar{K}_{IC} using the initial notch length a_0 and the maximum load. The critical crack tip opening displacement ($CTOD_c$) were also found to be size-independent (Table 2) for all the testing series except for the large beams of C1 series.

From Table 2, it can be observed (by comparing the K_{IC}^S values of C1 series vs. M1 series or M2 series vs. P1 series) that with the same water-cement ratio, the larger the size of the aggregate is the higher are the values of fracture toughness K_{IC}^S . Also, by comparing K_{IC}^S values associated with different compressive strength (or w/c ratio) of the same aggregate size, (M1, M2, and M3 series), it was observed that values of K_{IC}^S increase as the values of compressive strength increase. However, the increase of K_{IC}^S values are not directly proportional to the increase of compressive strength or water/cement ratio. It was noticed that values of $CTOD_c$ are about the same for the same aggregate size with different water/cement ratio. $CTOD_c$ increases with an increase of aggregate size.

It should be noted that unlike classically brittle materials, in cement based composites, cracks can propagate in a "stable" manner even beyond the peak load. This post-critical crack propagation (termed strain softening) can be predicted with a constant K_{IC}^S as shown in Fig. 5. The details are given in Refs. 24 and 25.

Some Predictions Based on the Proposed Fracture Criteria

Using the proposed fracture criteria K_{IC}^S and $CTOD_c$, it is possible to calculate the peak load for any given geometry [26]. To demonstrate this, a theoretical analysis on the three-point bend test was conducted. For this analysis it was assumed that concrete and cement paste had the same Young's modulus (3×10^6 psi) and the same K_{IC}^S value (1200 psi \sqrt{in}). Partly based on the test results reported here it was assumed that the elastic critical crack tip opening displacements ($CTOD_c$) for concrete and cement paste were respectively 0.0006 in. and 0.0001 in. From the proposed model, the peak load, and hence the values of the conventional \bar{K}_{IC} can be calculated. Fig. 6 shows the ratio of \bar{K}_{IC}/K_{IC}^S for different specimen sizes with notch-depth ratios ranging from 0.1 to 0.8 and depth-span ratio of four. It can be seen that \bar{K}_{IC} reaches its maximum values at $a_0/b = 0.2 \sim 0.3$. Such a trend has been reported from the test data by Carpinteri [27] (Fig. 7) and several other investigators [1, 2, 8, 10].

Fig. 8 gives the predicted results of notch-sensitivity, (i.e., the ratio of flexure strength of notched-specimen and failure flexure strength of unnotched specimens), for concrete and cement paste. It can be noticed that cement paste is more notch-sensitive than concrete. Similar notch-sensitivity results were also reported by Shah and McGarry [5] (Fig. 9) and other investigators [10, 27]. Size effect on modulus of rupture (MOR) of concrete is shown in Fig. 10. Note that MOR decreased with the increasing specimen depth as has been commonly observed from test results (Fig. 11).

Conclusion

1. Nonlinear crack growth effect in the process zone and inelastic behavior of concrete need to be considered in order to apply LEFM to concrete.
2. The fracture parameters K_{IC}^S (critical stress intensity factor) and $CTOD_c$ (critical crack tip opening displacement) calculated as proposed here, are found to be size-independent.
3. Based on concept of constant K_{IC}^S and $CTOD_c$, the reported size effect on conventional K_{IC} , modulus of rupture and notch-sensitivity can be accurately predicted.

Acknowledgment

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| Series | Cement | Fine Aggregate | Coarse Aggregate | Water | Max. Aggregate Size (in.) | Super-Plasticizer |
|-------------|--------|----------------|------------------|-------|---------------------------|-------------------|
| Concrete C1 | 1.0 | 2.6 | 2.6 | 0.65 | 0.75 | - |
| Mortar M1 | 1.0 | 2.6 | 0 | 0.65 | 0.1875 | - |
| Mortar M2 | 1.0 | 2.6 | 0 | 0.45 | 0.1875 | - |
| Mortar M3 | 1.0 | 2.6 | 0 | 0.25 | 0.1875 | 0.24 |
| Paste P1 | 1.0 | 0.5 | 0 | 0.45 | - | - |

* A small amount of sand was added to reduce the possibility of shrinkage cracking.

Table 1 - Mix-proportion and Maximum Aggregate Size of the Series Tested in this Program

| Series | Compressive Strength f'_c (psi) | Young's Modulus E ($\times 10^6$ psi) | K_{Ic}^S (psi $\sqrt{in.}$) | | | | $CTOD_c$ ($\times 10^{-3}$ in.) | | | |
|--------|-----------------------------------|--|--------------------------------|--------|-------|---------|----------------------------------|--------|-------|---------|
| | | | Large | Medium | Small | Average | Large | Medium | Small | Average |
| C1 | 3650 | 4.87 | 930.8 | 813.5 | 904.5 | 882.9 | 0.3845 | 0.7035 | 0.792 | 0.63 |
| M1 | 3942 | 3.68 | 631.1 | 654.0 | 644.1 | 643.1 | 0.324 | 0.463 | 0.302 | 0.363 |
| M2 | 5718 | 4.71 | 918.9 | 879.3 | 816.3 | 871.5 | 0.475 | 0.336 | 0.332 | 0.381 |
| M3 | 7950 | 5.41 | - | - | 963.5 | 963.5 | - | - | 0.394 | 0.394 |
| P1 | 4013 | 3.01 | 595.5 | 544.8 | 547.1 | 562.1 | 0.267 | 0.244 | 0.301 | 0.271 |

Table 2 - Relative material properties of all series.

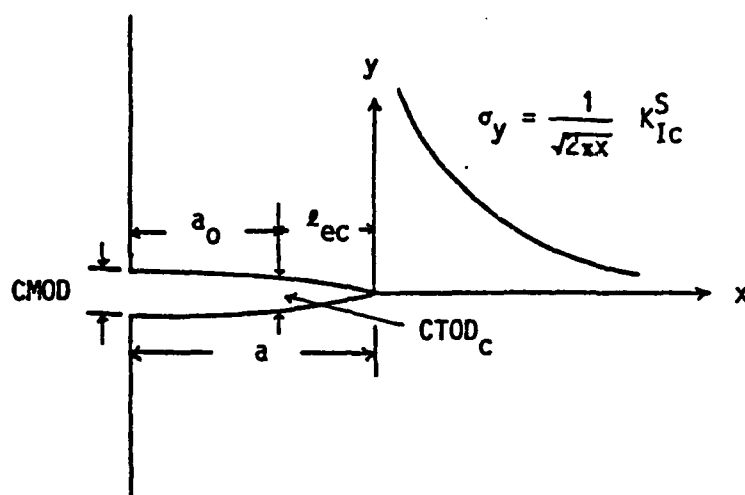


Fig. 1 - Effective Griffith Crack

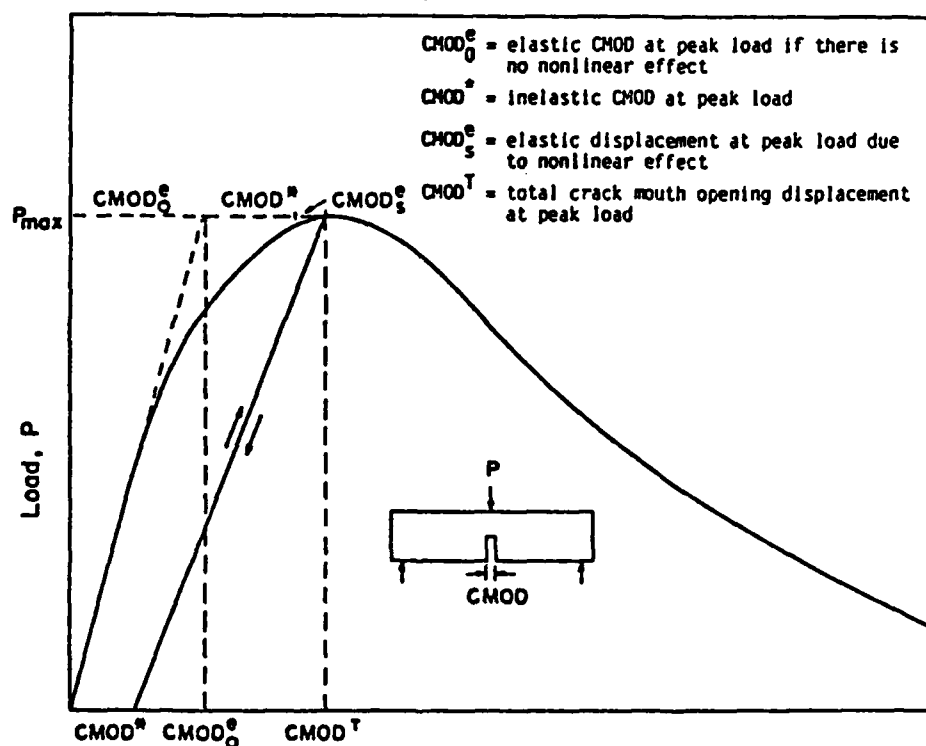
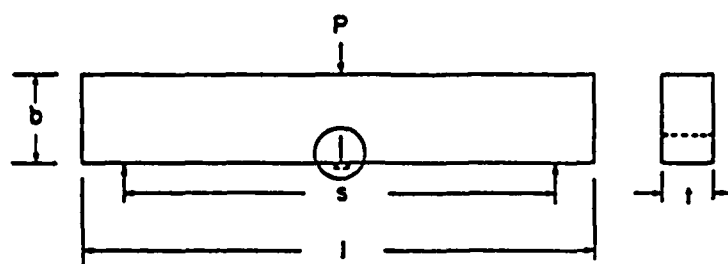
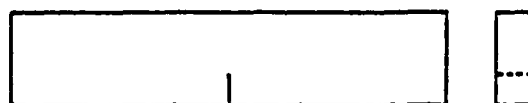
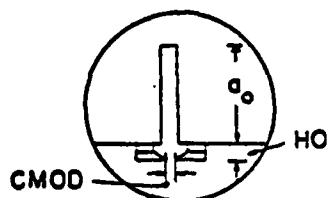


Fig. 2 - Compositions of CMOD due to Nonlinear Effect

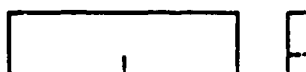


l = specimen length
 s = specimen loading span
 b = beam depth
 t = beam thickness
 HO = thickness of holder of clip gauge



$$s \times b \times t \times a_0$$

$$36" \times 9" \times 3.375" \times 3"$$



$$24" \times 6" \times 2.25" \times 2"$$



$$12" \times 3" \times 1.125" \times 0.88"$$

Fig. 3 - Dimension of Specimens

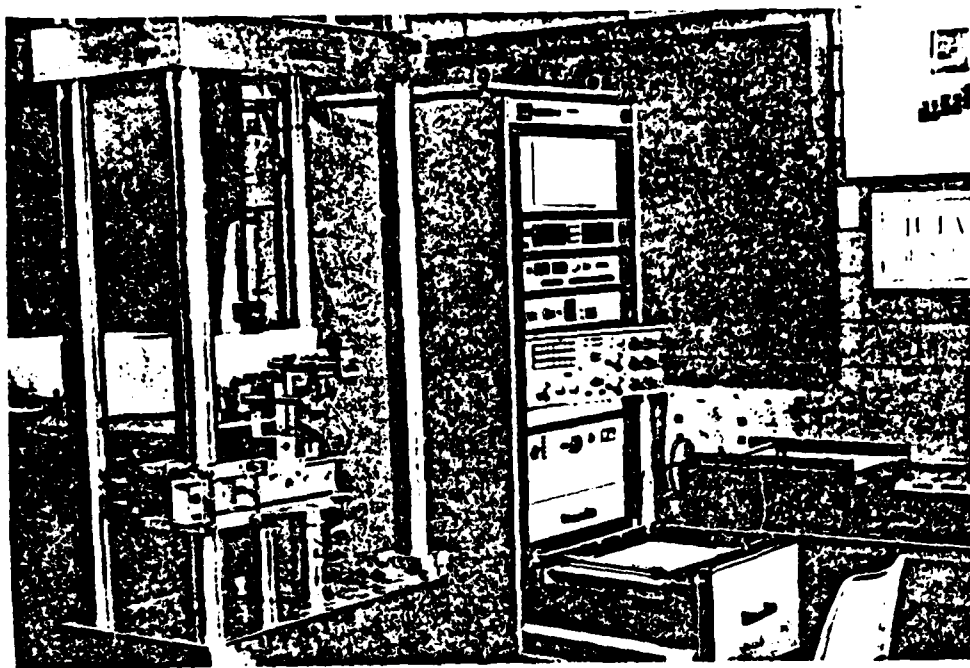


Fig. 4 - Experimental Set-Up - Small Specimens

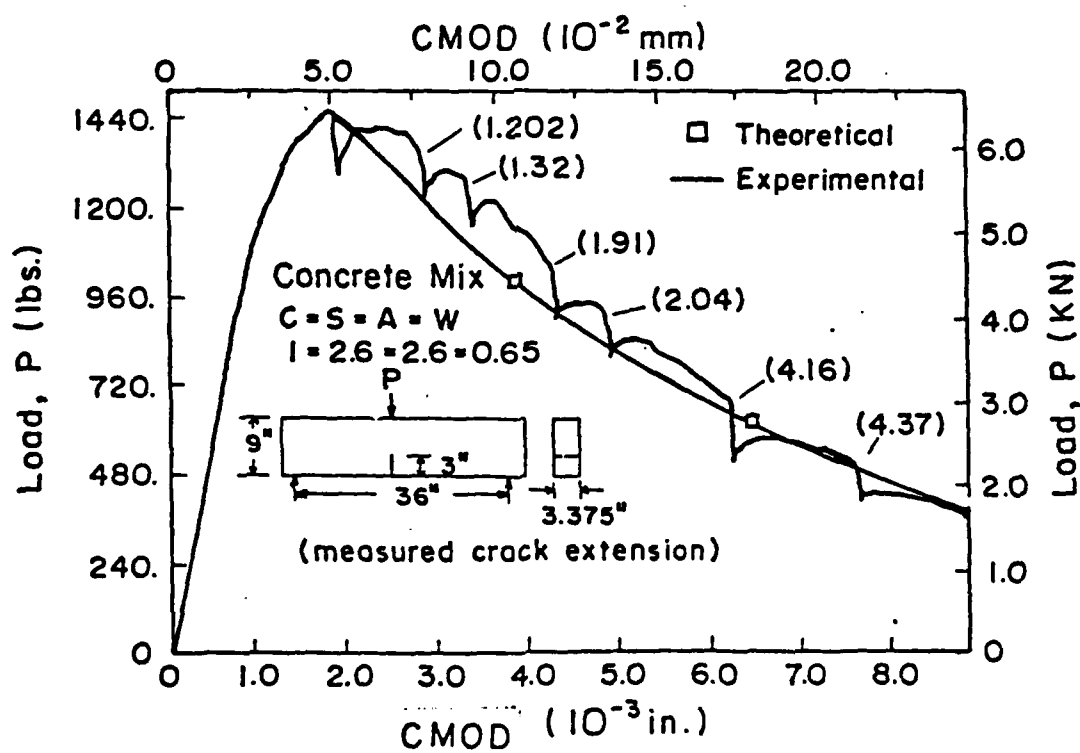


Fig. 5 - Theoretical Prediction and Experimental Results (CILI) for Post Critical Crack Propagation

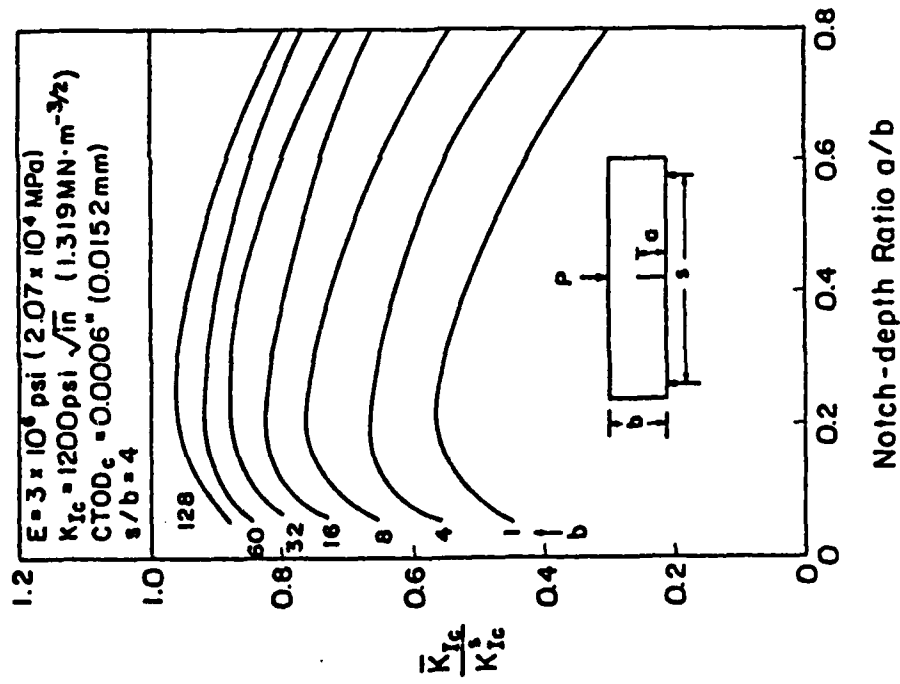


Fig. 6 - Theoretical Prediction of Notch-Depth Ratios on Conventional \bar{K}_{Ic}

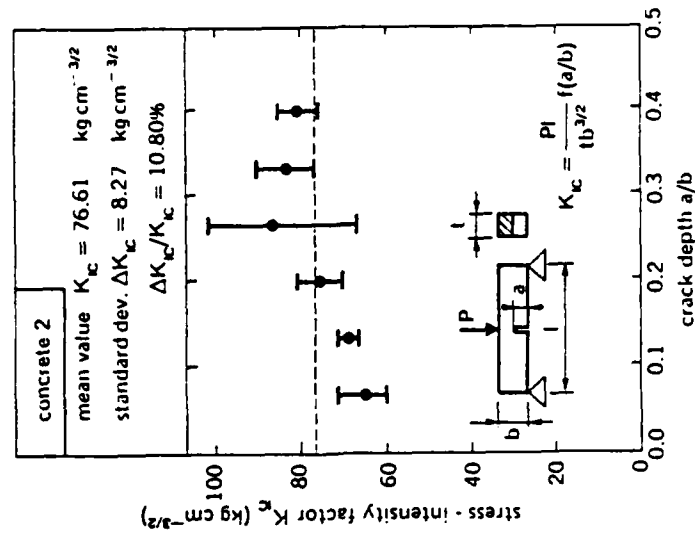


Fig. 7 - Experimental Results of Notch-Depth Ratios on Conventional \bar{K}_{Ic} Carpinteri [27].

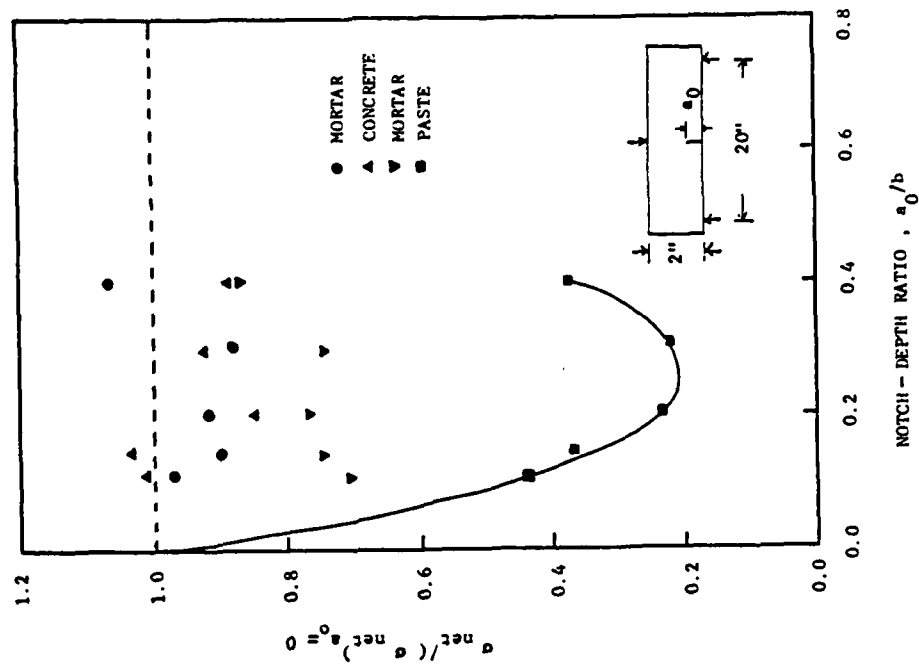


Fig. 9 - Experimental Results of Notch-Sensitivity - Shah and McGarry [5].

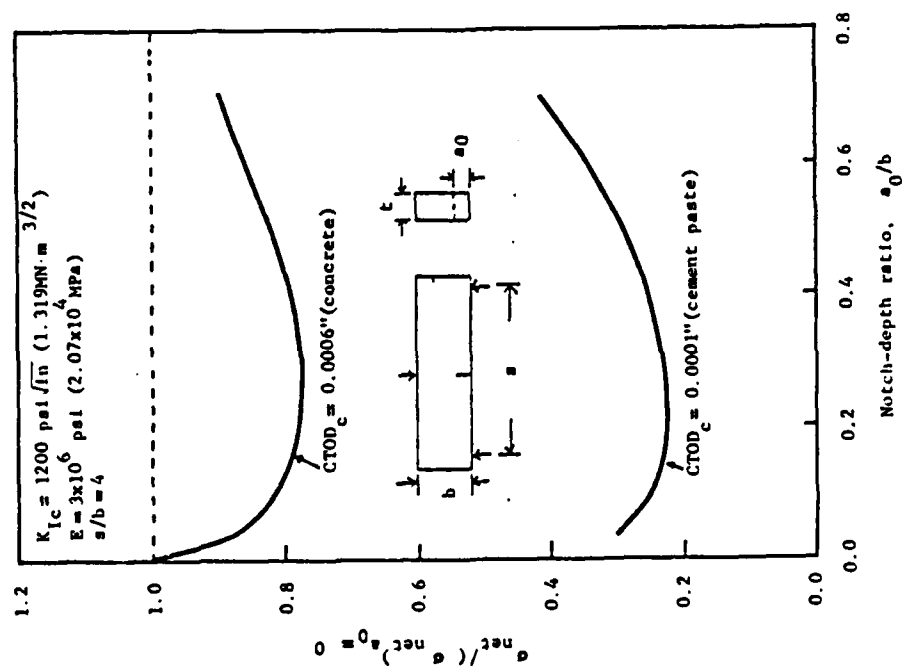


Fig. 8 - Theoretical Prediction of Notch-Sensitivity

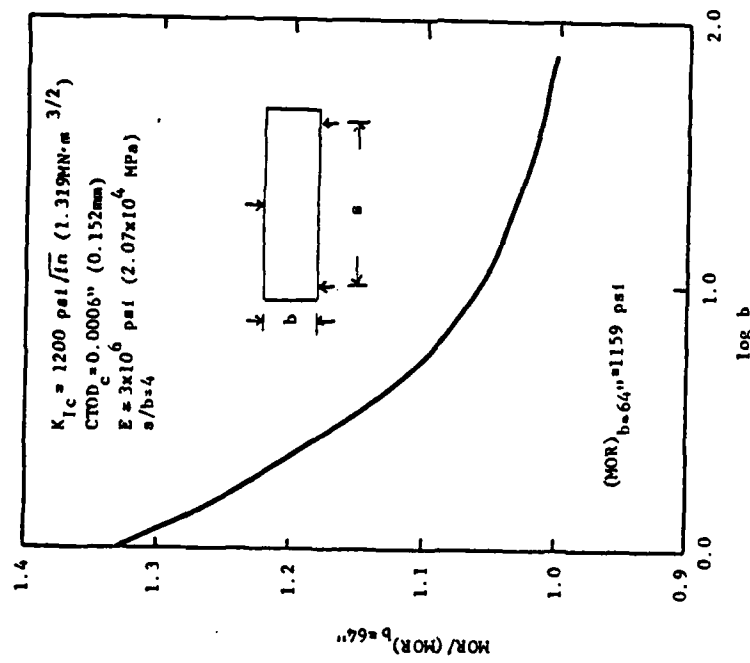


Fig. 10 - Theoretical Prediction of Size-Effect on Modulus of Rupture

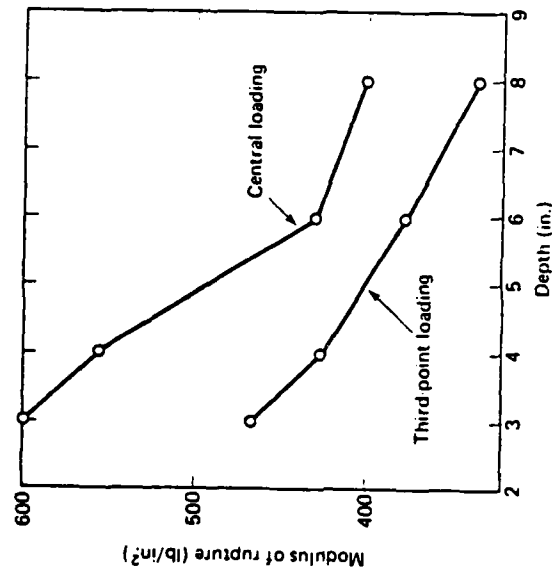


Fig. 11 - Experimental Results of Size-Effect on Modulus of Rupture - Wright [28]

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